REDUCING THE EARTH ENTRY VELOCITY FOR A COMET NUCLEUS SAMPLE RETURN MISSION

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Direct return to Earth after rendezvousing with a comet entails a very high entry velocity. Several methods for reducing the entry velocity, including using additional propellant on a direct return or using planetary gravity assists, are presented. The entry velocity can be reduced to a regime commensurate with current deep space sample return missions. The best method is a function of the mission parameters and target comet.

INTRODUCTION

Comets are thought to have formed in the outer solar system, condensing from the ancient solar nebula at the same time as the outer planets and their satellites. Due to their small sizes and cold storage in the far reaches of the solar system, comets could have preserved the chemical mixture from which the giant planets formed. Composed of ices, dust, and carbon-based compounds, they also played an important role in the evolution of the terrestrial planets by delivering a significant fraction of the elements important to life. Hence, the in situ study and return of cometary samples are among the highest priority goals of the planetary program.

The primary objective of a comet nucleus sample return (CNSR) mission is to return a sample of cometary volatiles to Earth for in-depth analysis. The sample needs to be maintained at cryogenic temperatures. The most accessible comets containing appropriate samples have the following orbital characteristics:
1. perihelion radius around 1 to 2 AU
2. aphelion radius around 5 to 6 AU (note: Jupiter orbits between 4.9 and 5.5 AU)
3. orbital period around 5 to 9 years

These are a subset of the short-period comets. The mission typically calls for rendezvousing with the comet (i.e., matching orbital state), collecting the sample, and returning to Earth.

A mission that departs a comet with these orbital characteristics and uses the minimum propellant necessary to intercept the Earth (hence, maximizes mass available to

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the spacecraft) will encounter Earth with an excess velocity (V_∞) of more than 8 km/s. The speed relative to the Earth at an altitude of around 125 km (considered to be the entry altitude) is greater than 13.6 km/s. We have no experience operating in this regime, and even testing with these conditions proves to be considerably challenging. The primary focus of this paper is to examine ways of reducing the entry velocity for a CNSR mission.

The relationship between V_∞ at Earth return and the entry velocity is shown in Figure 1. (The entry velocity is the velocity with respect to Earth. It does not account for any atmospheric rotation.) Also indicated in this figure are the velocities associated with other relatively near-term sample return missions. A V_∞ of 0 km/s is the border between being captured in orbit around Earth and being in a hyperbolic (escape) trajectory with respect to Earth. The corresponding entry velocity is 11.1 km/s. The Genesis mission skirts right around this boundary and returns with an entry velocity of 11.0 km/s. Stardust is a mission that flies by a comet – it does not rendezvous with it. The aphelion radius of the orbit that returns to Earth is 2.7 AU, much less than the aphelion radii of the short-period comets.

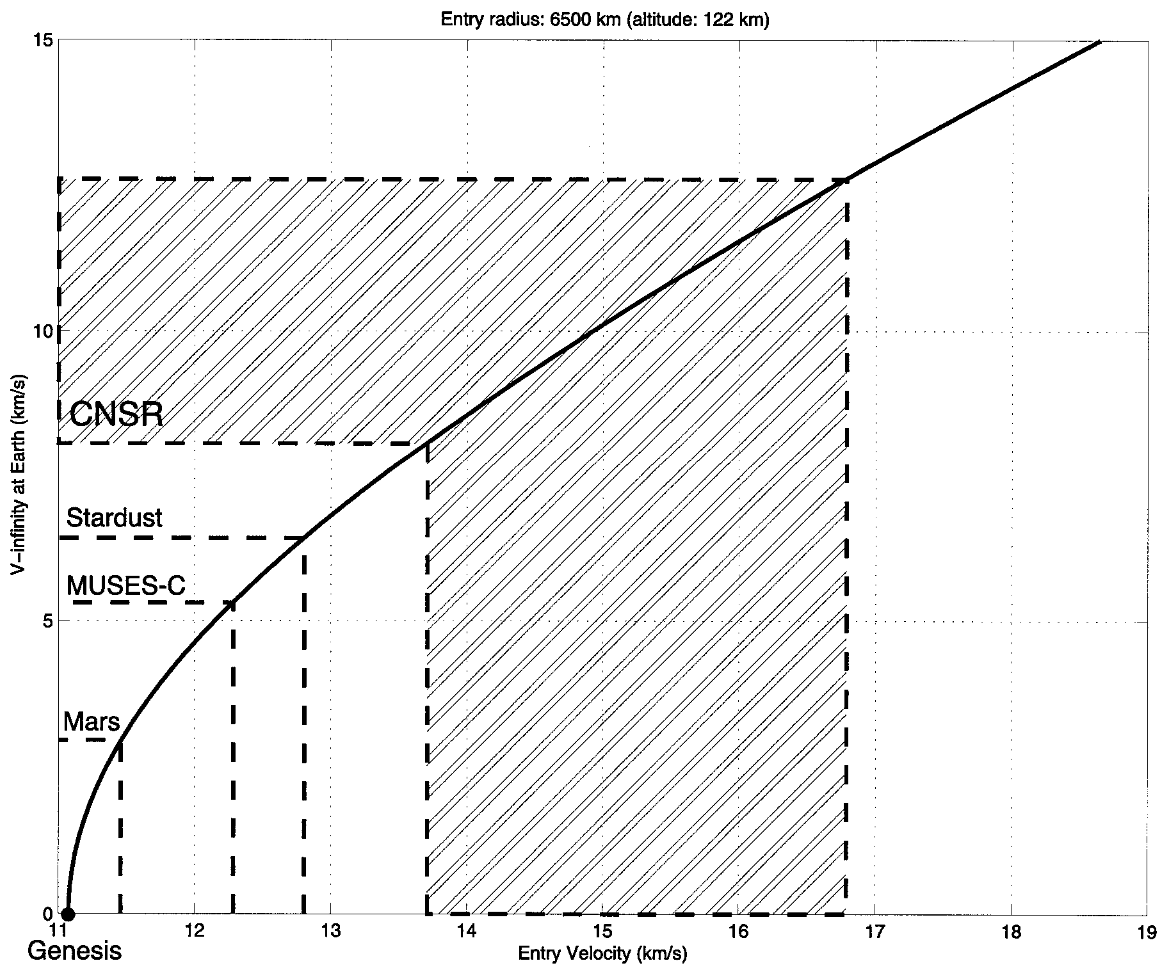

Figure 1 Relationship between V_∞ at Earth and Entry Velocity with Examples from Near-Term Sample Return Missions

No baseline target currently exists for a CNSR mission. The characteristics of trajectories to comets can vary significantly from one target to the next. Even for a given comet, the trajectory can be changed to accommodate various mission designs.[1,2] This paper does not focus on any one particular target. Examples are given for specific targets to demonstrate the concept being presented and to provide an idea of the effect on return V_∞, flight time, propellant mass, etc. We will try to draw some generalities, but we must keep in mind that the effects and sensitivities depend on the particular target, the trajectory that is being used as the "baseline," and the parameters of the mission.

A CNSR mission will likely use solar electric propulsion (SEP) to rendezvous with a comet.[2,3] A trade that remains open, however, is whether to use SEP or chemical propulsion to accomplish the departure from the comet and interception with the Earth. Advantages and disadvantages exist for each option. One of the major drivers of this trade is the amount of ΔV required. Because SEP has a much higher specific impulse than any chemical propulsion system, higher ΔVs tend to tip the advantage to using SEP for the return trajectory.

SAMPLE TRAJECTORIES

Low-Thrust Return

Characteristics of some representative trajectories that use SEP for both rendezvous and return are provided in Tables 1 and 2. The trajectories in Table 1 have launch dates in the 2005 through 2007 timeframe, and those in Table 2 launch between 2008 and 2012. The return V_∞s range from a little more than 8 km/s to a little over 12 km/s and one at 14.7 km/s.

We note that the flight times for these trajectories in Tables 1 and 2 are pretty close to integer multiples of a year, because both the launch and return occur close to when the Earth crosses the longitude of the perihelion of the comet's orbit. The return can often occur about one year earlier or later. Examples of this for trajectories to comets Tritton and Kowal 2 are included in Table 1. The return dates for the two trajectories to Tritton differ by about one year. The trajectory with the longer flight time has a lower return V_∞ and a higher spacecraft mass. The trajectory to Kowal 2 with the shorter flight time has a lower return V_∞, but the spacecraft mass is also lower.

Table 1

SEP TRAJECTORIES FOR A COMET NUCLEUS SAMPLE RETURN MISSION
Launch Dates: 2005-2007

Comet	Launch Date	Flight Time (yr)	Return V_∞ (km/s)	Launch C_3 (km^2/s^2)	Prop Mass[a] (kg)	S/C Mass (kg)
Finlay	2005, Aug 12	9.11	10.12	16.0	494	1148
Brooks 2	2005, Sep 3	8.10	8.38	11.9	613	1224
Wirtanen	2005, Nov 17	7.08	11.14	12.1	589	1239
Kopff	2006, June 23	9.06	8.45	16.3	605	1023
Churyumov-Gerasimenko	2006, Oct 26	8.06	9.73	11.4	595	1266
Tritton	2006, Dec 8	7.09	11.75	13.3	615	1155
Tritton	2006, Nov 13	8.14	9.33	11.8	644	1198
Kowal 2	2007, Nov 17	7.00	10.37	14.0	550	1184
Kowal 2	2007, Oct 28	8.07	11.14	12.6	568	1232

[a]10% propellant contingency has been added

Assumptions:

Launch
- Launch vehicle: Delta IV Medium
- 10% launch vehicle contingency
- no launch vehicle adapter

Power
- Solar array: HES, 17 kW, 1 AU, BOL
- Solar array degraded with time
- Spacecraft power: 450 W

Thrusters
- ST4-IPS V 4.0
- 1, 2, or 3 operating simultaneously
- Duty cycle: 90%

Propellant/tankage factor: 10%
Stay time at comet: 90 days
100 kg "dropped" at comet

Does not include a launch period or any forced coasts, including immediately following launch.

Table 2

SEP TRAJECTORIES FOR A COMET NUCLEUS SAMPLE RETURN MISSION
Launch Dates: 2008-2012

Comet	Launch Date	Flight Time (yr)	Return V_∞ (km/s)	Launch C_3 (km^2/s^2)	Prop Mass[a] (kg)	S/C Mass (kg)
Tempel 1	2008, May 7	8.07	10.34	19.7	667	1483
Tempel 2	2008, July 26	6.99	11.68	20.4	678	1434
Tsuchinshan 1	2009, Jan 9	7.98	11.17	20.4	659	1457
Tuttle-Giacobini-Kresak	2009, Mar 20	7.96	14.66	20.0	598	1537
Schwassmann-Wachmann 3	2009, June 3	7.99	12.37	21.5	573	1481
Forbes	2009, July 1	8.07	9.74	20.9	706	1383
Lovas 2	2010, Sep 8	8.00	8.59	21.2	566	1506
Neujmin 2	2011, Jan 29	8.03	10.02	22.3	464	1547
du Toit-Hartley	2011, Mar 25	6.94	12.35	17.7	549	1719
Brooks 2	2011, Sep 20	8.03	8.81	18.8	622	1582
Finlay	2012, Sep 19	9.04	10.60	22.5	548	1454

[a]10% propellant contingency has been added

Assumptions:

Launch
- Launch vehicle: Delta IV Medium+ (5,4)
- 10% launch vehicle contingency
- no launch vehicle adapter

Power
- Solar array: HES, 20 kW, 1 AU, BOL
- Solar array degraded with time
- Spacecraft power: 450 W

Thrusters
- Hi ISP NSTAR V 3.0
- 1, 2, 3, or 4 operating simultaneously
- Duty cycle: 90%

Propellant/tankage factor: 10%
Stay time at comet: 90 days
350 kg "dropped" at comet

Does not include a launch period or any forced coasts, including immediately following launch.

The trajectories presented in Tables 1 and 2 complete more than one revolution around the Sun prior to rendezvousing with the comet shortly after its perihelion passage. A representative trajectory to Brooks 2 is shown in Figure 2. The part of the trajectory drawn with a solid line in the figure indicates when the engines are thrusting. There is an optimal coasting period in this trajectory that lasts nearly one year between the initial and final thrusting arcs prior to rendezvous.

The return portion of the trajectory in Figure 2 includes a long coasting period around aphelion. During this time, the power output from the solar arrays is inadequate to operate the engines at their minimum power level. Once the power level has increased sufficiently as the spacecraft approaches the Sun, the engines turn back on and operate until about two months prior to reentry at Earth.

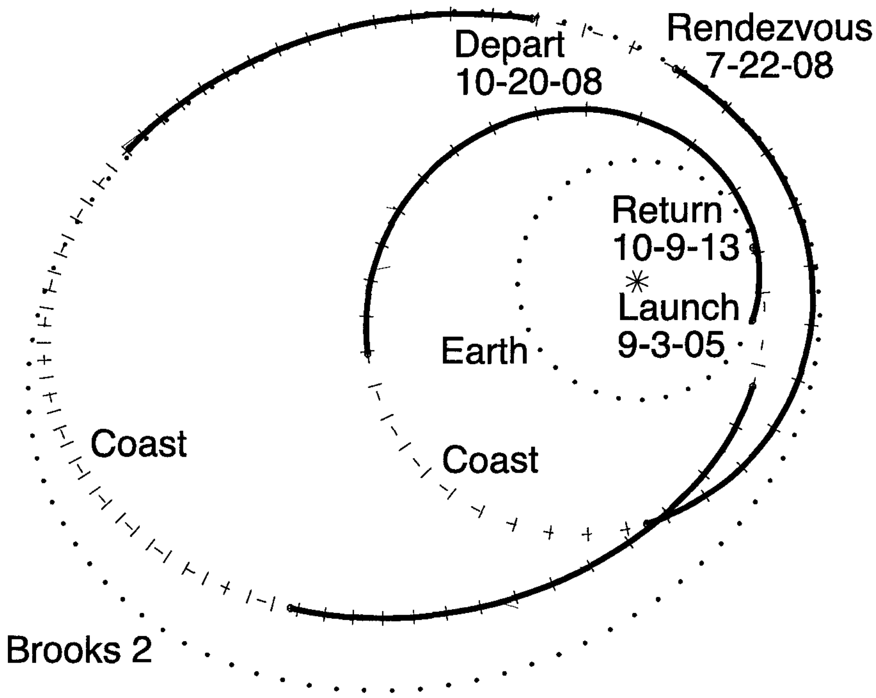

Figure 2 Sample Return Trajectory to Brooks 2

Impulsive Return

Characteristics of some representative trajectories that depart a comet and intercept Earth with impulsive ΔVs (i.e., using chemical propulsion) are presented in Table 3. We note how the total ΔV and arrival V_∞ vary for different Earth arrival dates from the same comet.

Table 3

IMPULSIVE RETURN TRAJECTORIES FOR A COMET NUCLEUS SAMPLE RETURN MISSION

Comet	Departure Date from Comet	Arrival Date at Earth	Flight Time (yr)	Return V_∞ (km/s)	Total ΔV (km/s)
Brooks 2	2010, May 30	2013, Sep 7	3.27	11.08	1.52
Brooks 2	2009, Apr 4	2012, Sep 9	3.43	8.71	2.24
Churyumov-Gerasimenko	2009, Oct 2	2014, Nov 13	5.12	9.80	0.99
du Toit-Hartley	2008, Dec 24	2012, Mar 30	3.26	7.83	1.98
du Toit-Hartley	2010, Jan 10	2013, May 3	3.31	10.46	1.15
du Toit-Hartley	2009, Mar 22	2014, May 3	5.12	9.72	1.82
Finlay	2008, Dec 2	2012, Oct 29	3.91	14.35	2.01
Finlay	2008, Dec 2	2013, Oct 18	4.88	12.01	1.00
Finlay	2008, Dec 2	2014, Oct 8	5.85	10.77	0.21
Kohoutek	2011, Feb 24	2013, Dec 21	2.82	9.55	1.97
Kopff	2012, Dec 1	2015, July 22	2.64	10.09	1.47
Kopff	2010, Nov 19	2014, July 7	3.63	10.20	2.07
Kowal 2	2010, Oct 2	2015, Nov 18	5.13	11.33	0.68
Kowal 2	2010, Oct 2	2014, Nov 18	4.13	10.38	1.36
Neujmin 2	2009, Sep 15	2013, Jan 31	3.38	9.53	1.59
Neujmin 2	2009, Mar 22	2014, Feb 9	4.89	11.40	1.15
Tritton	2009, Oct 2	2015, Jan 10	5.27	12.03	1.55
Tritton	2009, Oct 2	2014, Jan 6	4.26	11.85	2.36
Wirtanen	2008, Aug 13	2012, Dec 13	4.34	11.12	0.60

METHODS FOR REDUCING ENTRY VELOCITY

In addition to changing the arrival date at Earth by a year or so, methods to reduce the relative velocity (V_∞) at Earth include

1) maintaining the direct return, but using propellant to reduce the V_∞,
2) using planetary gravity assists in combination with propellant, and
3) using a lunar gravity assist.

Maintaining the direct return, but using propellant to reduce the V_∞

By maintaining the direct return, the total flight time is not significantly affected. The effectiveness of this method depends in part on the amount of coasting time that is available for thrusting on the return trajectory.

The trajectory in Figure 2 has a return V_∞ of 8.38 km/s. We can reduce this value by using more propellant. Figure 3 shows the amount of additional propellant mass required to reduce the V_∞ below 7.4 km/s. (The total mass departing the comet is 1312 kg.) As the V_∞ at Earth is reduced, the impact on mass performance becomes increasingly severe. Reducing the V_∞ significantly below 7 km/s requires a different type of trajectory.

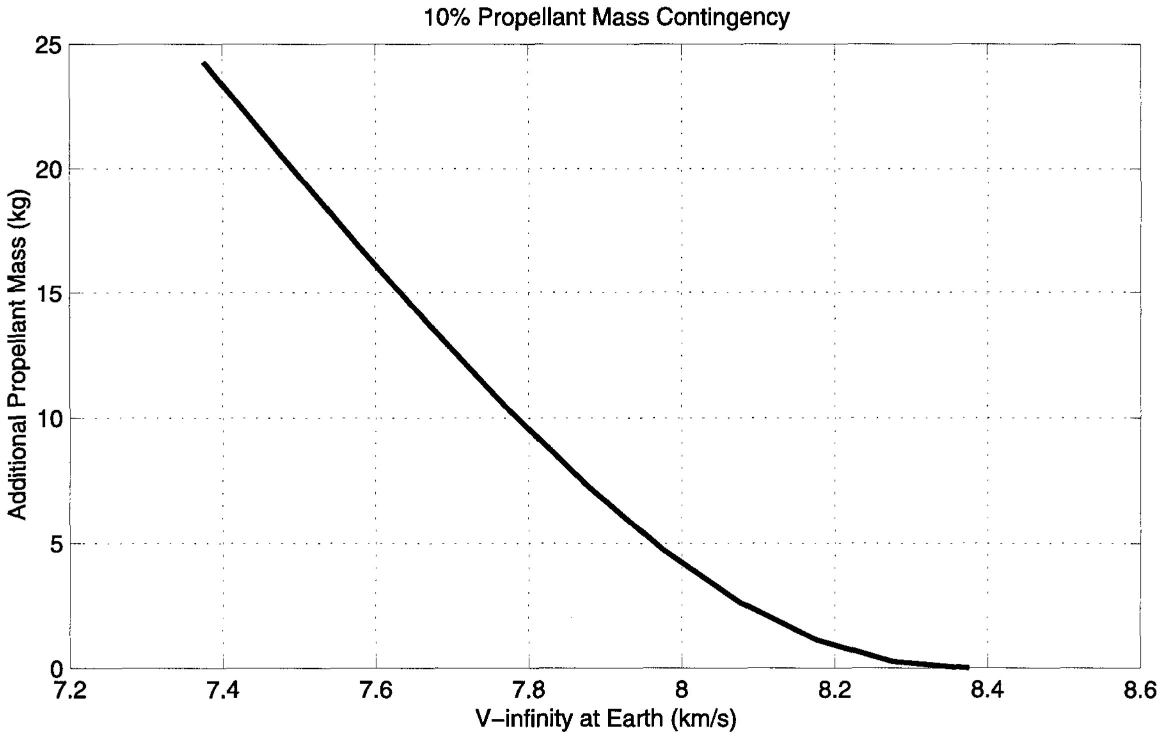

Figure 3 Additional Propellant Required to Reduce the V_∞ at Earth for the Sample Return Trajectory to Brooks 2

Sample return trajectories to the comet Tempel 1 were analyzed for the now defunct Deep Space 4 mission,[1] and an example is shown in Figure 4. The return V_∞ at Earth is 10.31 km/s. This trajectory has 8 or 9 months of coasting prior to Earth reentry, so a larger relative reduction in V_∞ can be accomplished compared to the trajectory in Figure 2. The additional propellant mass needed to reduce the V_∞ at Earth is shown in Figure 5. (The total mass departing the comet is 619 kg.) From this figure we see that the V_∞ can be reduced to a value well below that of Stardust and into a more tractable regime.

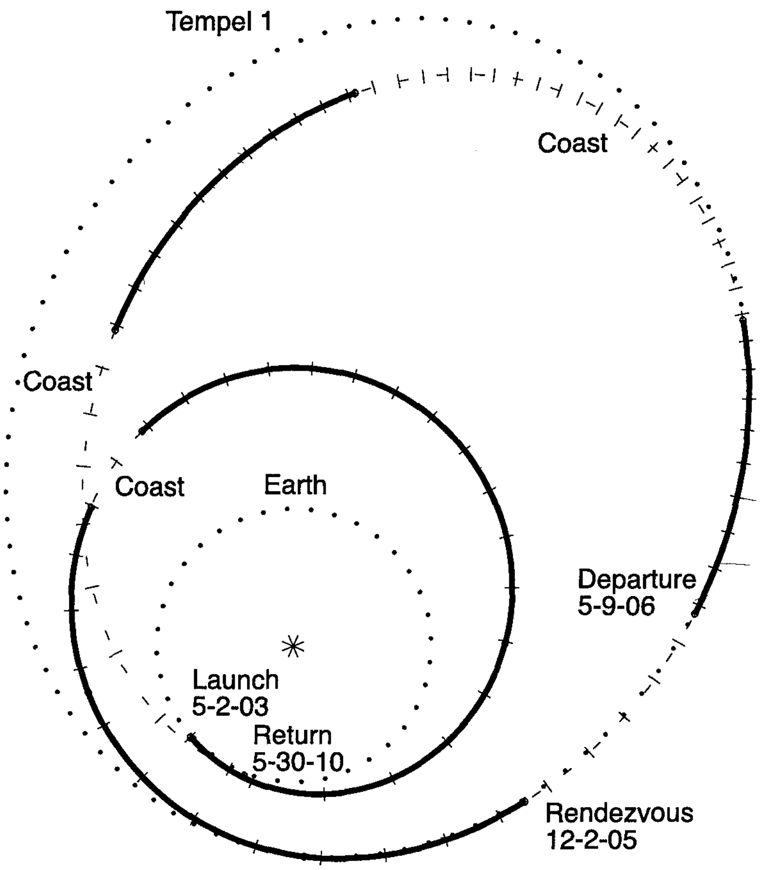

Figure 4 Sample Return Trajectory to Tempel 1

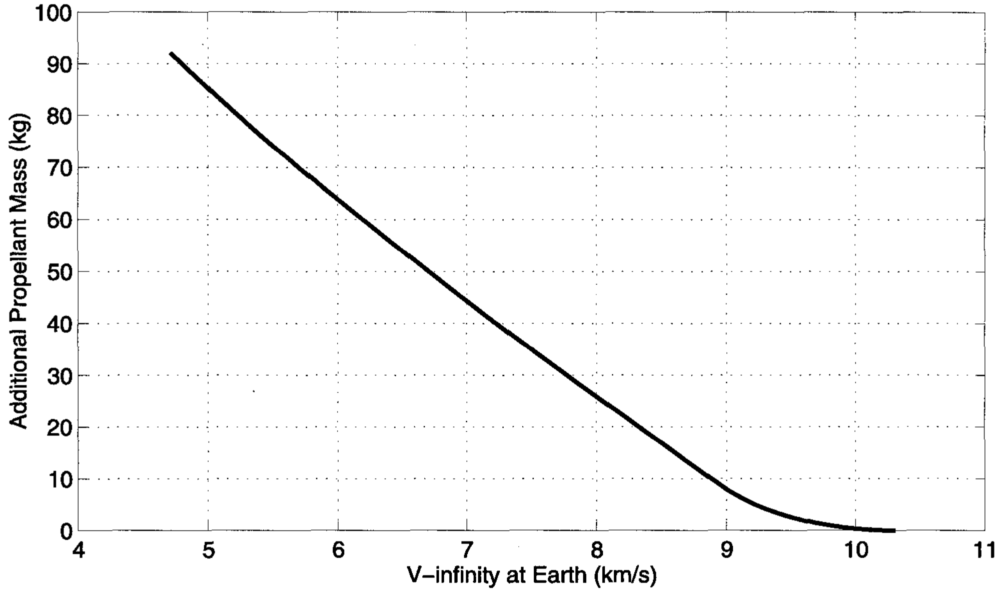

Figure 5 Additional Propellant Required to Reduce the V_∞ at Earth for the Sample Return Trajectory to Tempel 1

Using planetary gravity assists in combination with propellant

Using planetary gravity assists instead of a direct return will increase the flight time but can substantially reduce the arrival V_∞ at Earth with relatively modest increases in propellant. The gravity assists will be accompanied by propulsive maneuvers, which can be accomplished with either SEP or chemical propulsion. Because trajectories with impulsive maneuvers are easier to design, the first step is to construct various impulsive trajectories. Low-thrust trajectories will take on slightly different forms than the impulsive trajectories; however, the relative merits of the trajectories based on return V_∞, total ΔV (propellant usage), and flight time will be similar.

For the mission shown in Figure 4, a direct return has a minimum impulsive ΔV of 1.54 km/s and arrives at Earth with a V_∞ of 10.7 km/s. By slightly altering the direct return, we can arrive at Earth with a V_∞ of 8.8 km/s by increasing the total ΔV to 2.01 km/s. (The departure date from the comet is constrained to be no earlier than May 9, 2006.)

If we use the first Earth encounter as a gravity assist (EGA), we can return to Earth about 2 years later with a V_∞ a little over 5 km/s. Unlike most parameters, this value of V_∞ after a 2:1 EGA is very consistent for returning from all of the short-period comets. The total ΔV for the return from Tempel 1 with a 2:1 EGA is around 2.5 km/s.

A Venus gravity assist (VGA) can be used to reduce the return V_∞ at Earth even further; however, a substantial amount of ΔV is needed to directly reduce the perihelion of the trajectory in order to encounter Venus. Another way to incorporate a VGA is to use an EGA to reduce the perihelion for the Venus encounter. The flight time increases to accommodate the phasing of the flybys, but the return V_∞s can be substantially lowered with only modest increases in total ΔV.

A summary of impulsive returns from Tempel 1 is provided in Table 4. A similar study was done for impulsive returns from Wirtanen. The results are presented in Table 5. The data in Table 5 are plotted in Figure 6.

Table 4

SUMMARY OF IMPULSIVE RETURNS FROM TEMPEL 1

Type	Return V_∞ (km/s)	Total ΔV (km/s)	Return Date
Direct	10.7	1.54	2010, May 30
Direct	8.8	2.01	2010, May 28
EGA	5.3	2.57	2012, July 5
EGA	5.1	2.50	2012, April 16
VGA	3.3	6.45	2011, Jan 22
VGA	5.7	5.40	2012, May 28
EVGA	4.5	2.39	2012, Dec 21
EVGA	4.0	2.54	2012, Dec 10

Departure date from comet constrained to be no earlier than May 9, 2006.

Table 5

SUMMARY OF IMPULSIVE RETURNS FROM WIRTANEN

Type	Return V_∞ (km/s)	Total ΔV (km/s)	Return Date
Direct	11.1	0.60	2012, Dec 13
Direct	9.0	1.47	2012, Dec 8
EGA	5.2	2.24	2015, Jan 12
EGA	5.1	2.08	2014, Oct 29
EVGA	2.9	3.87	2016, Sep 29
EVGA	3.4	3.70	2015, Oct 2
EVGA	4.6	2.34	2016, Feb 22
EVGA	3.9	1.92	2016, June 28
EVGA	6.0	1.52	2016, July 17

Departure date from comet constrained to be no earlier than Aug 13, 2008.

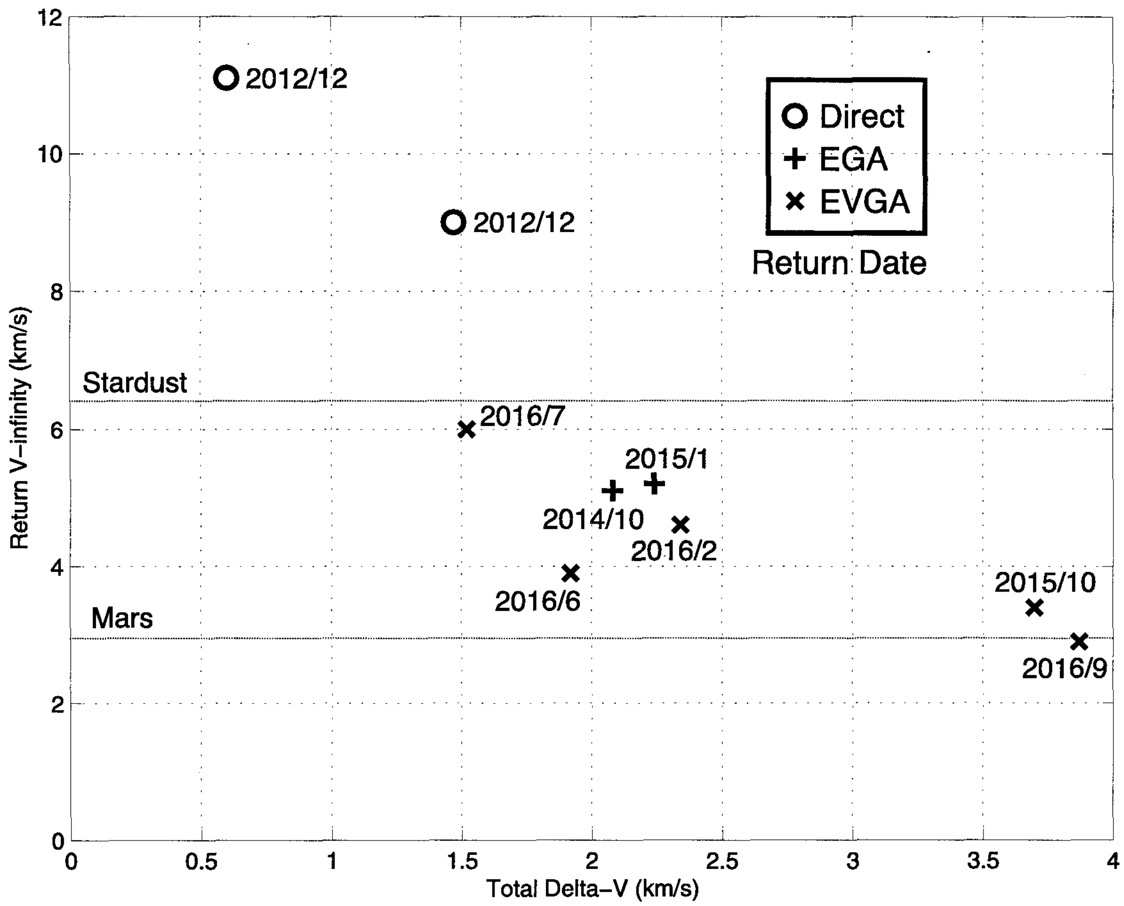

Figure 6 Summary of Impulsive Returns from Wirtanen

Using a lunar gravity assist

Using a lunar gravity assist is often suggested as a method for reducing the entry velocity; however, a lunar gravity assist as part of a direct return and Earth entry can have at best a very minor effect on the entry velocity. The high relative speed limits the Moon's ability to alter the trajectory. Even with the ideal phasing conditions, the entry velocity at Earth is reduced less than 0.1 km/s if the V_∞ is 5 km/s and less than 0.05 km/s if the V_∞ is 10 km/s.

METHODS FOR MODIFYING ENTRY PROFILE

In addition to reducing the relative velocity at Earth encounter, the entry heating conditions can be alleviated by modifying the entry profile. For example, instead of the typical entry vehicle with heat shield, a ballute could be used to substantially reduce the peak heating rate and total heat load associated with the entry.[4]

Another method of modifying the entry profile is to capture into orbit around Earth and then reenter. In this case the final entry velocity is less than that corresponding to Earth escape (11.1 km/s). As shown in Figure 7, the ΔV necessary for an impulsive capture at Earth can be substantial. A rendezvous with Earth and capture could also be accomplished using SEP, but in addition to an increase in propellant mass, the total flight time would be significantly longer. Instead of using chemical propulsion or SEP to capture at Earth, we could use the atmosphere to aerocapture. A problem associated with aerocapture for a CNSR mission is the heating that will occur, but again a ballute could be used to alleviate the heating conditions.[5]

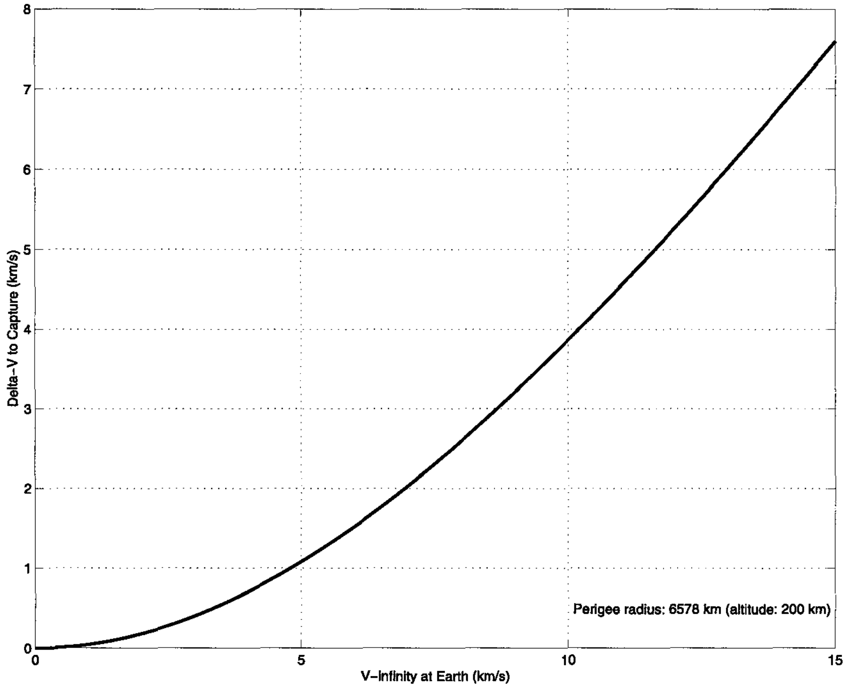

Figure 7 Required ΔV for Impulsive Capture at Earth

Once in orbit around Earth, the final entry velocity could be reduced even further using aerobraking and perhaps even a lunar gravity assist, depending on the size of the initial capture orbit.

SUMMARY

Reducing the entry velocity at Earth will decrease the mass available for the spacecraft (i.e., the non-propellant mass) and/or increase the total flight time. Any option that increases the propellant mass is likely to be a bigger detriment to using chemical propulsion for the return trajectory than to using SEP.

If the nominal V_∞ is close to an acceptable value and coasting time is available for thrusting on the return trajectory, it may be possible to thrust more on the direct return to sufficiently lower the V_∞. The total flight time won't change much.

Additional thrusting on a direct return is often inefficient. If spacecraft mass becomes an issue or if the V_∞ can't be reduced sufficiently by thrusting on the direct return, a gravity assist could be used to help lower the V_∞ with a more reasonable increase in propellant mass, but with a corresponding increase in flight time. An EGA with a 2-year return may be a good option if a V_∞ of 5 km/s is low enough. Using a VGA could reduce the V_∞ even further, but with the cost of a longer flight time and a closer approach to the Sun – a potential problem considering the cryogenic maintenance requirement.

We gave examples for some particular comets in this paper. While these examples demonstrated some general trends, we must keep in mind that the sensitivities and mission impact of the methods described can vary significantly from target to target.

ACKNOWLEDGMENT

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